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Recent results from a study of thorium lung burdens and health effects among miners in China

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Abstract

The purpose of this study was to obtain more information about health effects among the dust-exposed male miners of Bayun Obo Rare-Earth and Iron Mine, China. From 2390 male miners from the seven dust-generating workshops of the mine, 136 dust-exposed miners were randomly selected for study. Of these, 64 men were from the high-dust-generating workshop and 72 from the lower-dust-generating workshops; the latter group was used as an internal control. Physical measurements and medical examinations were carried out on each of these 136 men. The average measured thorium lung burden for the high-dust-exposure miners was significantly greater than that for the group of lower-exposure miners, and the incidence of severe breathlessness and pneumoconiosis of stage 0^+ was also significantly raised in the high-exposure group relative to the low-exposure group. An epidemiological study of lung cancer mortality among all the miners and staff of this mine was also carried out. This showed significantly raised levels of lung cancer mortality in both exposed miners and unexposed workers when compared with the Chinese population, and the level in exposed miners was significantly higher than that in unexposed men. The general high rate of lung cancer mortality in the workers of the mine is attributed to high levels of cigarette smoking, and the raised rate in the exposed miners relative to the unexposed workers to inhalation of silica- and thorium-bearing dusts and thoron progeny.

1. Introduction

During the period from 15 December 1993 to 15 August 1994, an investigation into the thorium lung burdens and consequent health effects among the miners of Bayan Obo Rare-Earth and Iron Mine, China, was carried out. This project was supported by the IAEA. The purpose of the study was to obtain more information about the health effects, both stochastic and non-stochastic, among the dust-exposed miners in this mine.

Bayan Obo Rare-Earth and Iron Mine is one of the largest rare-earth/iron mines in the world. It has been in operation for over 40 years. Its ore contains not only iron and rare-earth elements, but also silicon dioxide (silica) at a concentration of 10% by weight and thorium at a concentration of 0.04% by weight.

The air concentrations of thorium-containing rare-earth and iron ore dusts in individual workshops are quite high. For example, in 1993, in the crushing workshop, concentrations were in the range of 1.6–74.0 mg m^{-3}. In another six dust-generating workshops, the average air concentrations of dusts were in the range 1.2–16.4 mg m^{-3}. In 1991, the air concentration of short-lived thoron (^{220}Rn) daughters in the crushing workshop was in the range of 2.7–736 $\times 10^2$ MeV L^{-1}, six to 18 times higher than that of short-lived radon (^{222}Rn) daughters in the same locations. In control areas, the air concentration of short-lived thoron daughters was in the range of 2.0–4.4 $\times 10^2$ MeV L^{-1}. High gamma-ray exposures only occurred in mining workshops; the highest dose-rate there was 1 μGy h^{-1}.

The total number of miners and staff at this mine is 7558 (5476 males and 2080 females). Among them, 2903 (2390 males, 513 females) are dust-exposed miners; they are all working in the dust-generating workshops.

In this study, 136 dust-exposed men were randomly selected from the 2390 male miners from the seven dust-generating workshops. Among them, 64 were from the high-dust-generating workshop—the crushing workshop. The other 72 miners were from the six lower-dust-generating workshops: 20 were from the main mine workshop, 17 from the eastern mine workshop, ten from the train-transportation workshop, ten from the bus-transportation workshop, seven from the highway workshop and eight from the electrical engineering workshop.

Physical measurements and medical examinations were carried out on each of the above-mentioned 136 male dust-exposed miners.

An epidemiological study of lung cancer mortality among all the miners and staff from this mine was also carried out.

2. Methods

2.1. Radioactivity measurements

The measurement of radioactivity *in vivo* consisted of a thoron-breath measurement. Radioactive thoron (^{220}Rn) gas in exhaled breath was collected and measured by alpha particle counting of the longer-lived decay products of thoron. It is based on electrostatic collection on to a negatively charged Mylar disk of the daughter ^{212}Pb, 85–88% of which is positively charged. The exhaled thoron activity is expressed as the activity of freely emanating ^{224}Ra (the parent of ^{220}Rn), that would support the ^{220}Rn concentration measured at the subject's mouth [1]. A conversion factor of 3.7 Bq emanating ^{224}Ra equivalent activity at the mouth to 37 Bq ^{232}Th was used to estimate the thorium lung burden [2]. The true amount of thorium in any case will tend to be higher, because there may not have been time for equilibrium between ^{232}Th and ^{212}Bi to be established, because intermediate members of the decay chain, particularly ^{228}Ra and ^{224}Ra, may have left the thorium in the lungs, and because of exhalation of ^{220}Rn. In our situation, an under-estimate by a factor of two was considered and applied [3], based on the experience of Stebbings [4].

2.2. Medical examinations

The general medical protocol includes a complete physical examination, testing of hepatic and haematological parameters, respiratory symptoms, questionnaire recordings, chest x-ray and pulmonary function tests. Chest radiographic results were read by two senior radiologists in a

Table 1. Comparison of ages between the two groups.

Group	Number of miners	Age range (y)	Average age ($\pm$SE) (y)	t	P
Crushing	64	30–57	49.3 ± 0.6	1.44	>0.05
Internal control	72	34–59	48.0 ± 0.7		

Table 2. Comparison of dust-exposure histories between the two groups.

Group	Number of miners	Range of length of dust exposure (y)	Average length of dust exposure ($\pm$SE) (y)	t	P
Crushing	64	8–36	28.3 ± 0.8	1.35	>0.05
Internal control	72	17–36	27.0 ± 0.6		

blind manner (i.e. not telling them about each examinee's thorium lung burden estimate before reading the chest radiographic result).

In order to determine the relationship between the thorium lung burden estimates and the effects upon the health of the examinees, the above-mentioned 136 miners were divided into two groups, the crushing group (64 miners) and an internal control group (72 miners from the other six workshops). This was because the difference between the average thorium lung burden estimates of the two groups was very significant. In particular, among the 72 miners of the internal control group, none had a thorium lung burden estimate higher than 1.84 Bq, the lower limit for the detection of thorium contamination in the miners of Bayan Obo rare-earth and iron mine. Based on different ranges of thorium lung burden estimates, the crushing group was divided into three groups: crushing group 1, crushing group 2 and crushing group 3.

3. Results

3.1. Comparison of background details of the miners

Comparison of age between the crushing group and the internal control group. The age ranges of the two groups are similar; there was no statistically significant difference between the average ages of these two groups (table 1).

Comparison of dust-exposed history between the crushing group and the internal control group. There is no statistically significant difference in the dust-exposure histories between the two groups (table 2).

Comparison of smoking habits between the crushing group and the internal control group. There are no statistically significant differences between the percentage of smokers, smoking history and cigarettes smoked per day for the two groups (table 3).

The results presented in the above three tables show that the extraneous effects of factors such as age, dust-exposure histories and smoking habits have been avoided.

3.2. Results of radioactivity measurements and medical examinations

Comparison of thorium lung burden estimates between the crushing group and the internal control group. The difference between the average thorium lung burden estimates for the two groups is statistically significant (table 4).

Table 3. Comparison of smoking habits between the two groups.

Group	Number of miners	Number of smokers	(%)	Smoking history (±SE) (y)	Average number of cigarettes (d^{-1}) (±SE)
Crushing	64	50	78.13	26.7 ± 0.9	17.8 ± 0.9
Internal control	72	55	76.40	25.8 ± 0.6	19.3 ± 0.9
t			($\chi^2 = 0.058$)	0.858	1.13
P			>0.05	>0.05	>0.05

Table 4. Comparison of thorium lung burden estimates between the two groups.

Group	Number of miners	Thorium lung burden estimates (±SE) (Bq)	t	P
Crushing	64	1.71 ± 0.18	2.364	<0.01
Internal control	72	0.58 ± 0.04		

Table 5. Comparison of thorium lung burden estimates between the crushing group and the other six workshops.

Workshop	Number of miners	Thorium lung burden estimates (Bq)		
		Range	Mean ± SE	P^a
Crushing	64	0.13–7.26	1.71 ± 0.18	
Main mine	20	0.11–1.25	0.64 ± 0.08	<0.002
Eastern mine	17	0.20–1.32	0.59 ± 0.07	<0.005
Train transportation	10	0.13–0.66	0.39 ± 0.06	<0.01
Bus transportation	10	0.13–0.92	0.45 ± 0.09	<0.01
Technical electricity	8	0.26–1.45	0.68 ± 0.12	<0.05
Highway	7	0.20–1.39	0.62 ± 0.09	<0.05

[a] Statistical significance of the difference between the average thorium lung burden of the miners in each of the other six workshops compared with that of the crushing workshop.

Comparison of thorium lung burden estimates between the crushing workshop and the other six workshops composing the internal control group. Only in the crushing workshop group of miners were there dust-exposed miners (37.5%) having a thorium lung burden estimate higher than 1.84 Bq [5], the assumed lower limit for the detection of thorium contamination of the miners in this mine as compared to the background level (table 5).

Table 5 also shows that the difference between the higher average thorium lung burden estimate for the miners from the crushing workshop and that of any other workshop is statistically significant.

Comparison of respiratory symptoms between the miners in the crushing group and the internal control group. The incidence of severe breathlessness in the 64 miners of the crushing workshop group is significantly different from that of the 72 miners in the internal control group (32.8% versus 13.9%; $\chi^2 = 6.895$, $P < 0.001$). The differences in the incidence of chronic cough and chronic phlegm between these two groups are not statistically significant.

Table 6. Comparison of respiratory symptoms between the crushing group and the internal control group.

	Crushing workshop ($n = 64$)		Internal control ($n = 72$)	
Symptoms	Number of cases	%	Number of cases	%
Chronic cough	27	42.2	28	38.9
Chronic phlegm	29	45.3	28	38.9
Breathlessness				
Light	15	23.4	26	36.1
Medium	16	25.0	13	18.1
Severe	21	32.8	10	13.9

Table 7. Comparison of radiographic findings in the crushing group and the internal control group.

Group	Number of miners	Number of cases of pneumoconiosis stage 0^+	Incidence (%)	P
Crushing	64	12	18.75	<0.01
Control	72	1	1.40	

Table 8. Thorium lung burden estimates for the three crushing groups and the internal control group.

		Thorium lung burden estimates (Bq)	
Group	Number of miners	Range	Mean (±SE)
Crushing group 1	36	0.13–1.45	0.82 ± 0.07
Crushing group 2	10	1.52–2.18	1.74 ± 0.07
Crushing group 3	18	2.38–7.26	3.76 ± 0.29
Internal control	72	0.11–1.45	0.58 ± 0.04

Comparison of lung function disorder incidence between the miners in the crushing group and the internal control group. Using a Discom-21 spirometer, lung function tests were carried out on each of the 64 miners of the crushing group and the 72 miners of the internal control group. Only one case of lung function disorder was apparent (both were restrictive type) in each group. The incidence in these two groups was 1.56% and 1.38% respectively.

Comparison of radiographic findings in the crushing group and the internal control group. The incidence of pneumoconiosis of stage 0^+ in the miners of the crushing group is 18.75%, while the incidence in the miners of the internal control group is 1.4%. The difference between them is highly statistically significant ($\chi^2 = 11.81$, $P < 0.01$). This difference suggests a causative association between dust exposure at the mine and pneumoconiosis. The causative agent may be silica (typically 10% by weight in the dust), thorium (0.04% by weight in the dust) or other components, or some combination of these components acting synergistically.

Possible threshold values of thorium-containing ore dusts in inducing pneumoconiosis stage 0^+ in the miners in the crushing group. The range of the thorium lung burden estimates of the 12 miners suffering from pneumoconiosis 0^+ was from 1.22 to 3.71 Bq. 1.22 Bq of thorium is equivalent to 755.5 mg of thorium-containing ore dusts (because thorium is present at a level

Table 9. Comparison of haematological parameters of the four groups of miners. (Hb—haemoglobin; WBC—white blood cell.)

Group	Number of miners	Hb (%)	WBC (counts mm^{-3})	Neutrophil (%)	Lymphocyte (%)
Crushing group 1	36	13.9 ± 0.08	6489 ± 224	68.0 ± 1.3	32 ± 1.3
Crushing group 2	10	13.7 ± 0.14	6160 ± 238	69.0 ± 1.6	30 ± 1.6
Crushing group 3	18	13.5 ± 0.13	7211 ± 247	68.1 ± 1.4	32 ± 1.4
Internal control	68	14.1 ± 0.07	6865 ± 266	69.0 ± 0.9	31 ± 0.9

Table 10. Comparison of hepatic parameters of the miners of the four groups. (AKP—alkaline phosphatase; TTT—thymol turbidity test; GPT—glutamic pyruvic transaminase; TFT—thymol flocculation test.)

Group	Number of miners	TTT	GPT	AKP	TFT
Crushing group 1	36	5.0 ± 0.5	16.8 ± 0.4	18 ± 0.7	Negative
Crushing group 2	10	5.0 ± 0.5	19.6 ± 1.5	19 ± 2.2	Negative
Crushing group 3	18	4.5 ± 0.2	17.8 ± 0.9	19 ± 1.4	Negative
Internal control	68	5.0 ± 0.1	16.0 ± 0.4	28 ± 1.6	Negative

of 0.04% by weight in the ore dust). This figure is quite near the possible threshold value of thorium-containing ore dusts (803–940 mg) in inducing pneumoconiosis of stage 0^+ reported by Chen *et al* [6].

Estimated thorium lung burdens and relationship to haematologic and hepatic parameters. For the purpose of making comparisons between the haematologic and hepatic parameters of miners having different thorium lung burden estimates, the 64 miners of the crushing group were divided into three groups of different ranges and different averages of thorium lung burden estimates: crushing group 1, crushing group 2 and crushing group 3. They were each compared with the internal control group and each other.

The measurement results of the haematological parameters of the above-mentioned four groups are listed in table 9.

Table 9 shows that the average values of all these four haematological parameters were within normal ranges. There is no statistically significant difference between the parameters of any two groups.

Table 10 shows that the average values of all these four hepatic parameters are within normal ranges. There was no statistically significant difference between the parameters between any two groups. This is because the rate of absorption of thorium dioxide in blood is about 0.0001 d^{-1}, which means that the amount of relatively insoluble thorium entering the blood circulation system and depositing in the liver must be very small. In addition, in this group the highest thorium lung burden is only 7.26 Bq.

3.3. Results of an epidemiological study of lung cancer in the miners of Bayan Obo Rare-Earth and Iron Mine

Lung cancer mortality among dust-exposed miners and dust-unexposed miners. An epidemiological study of lung cancer mortality in both the dust-exposed miners and dust-unexposed miners was carried out in 1994. The main results are listed in table 11. The total person-years for the dust-exposed miners and the dust-unexposed miners are 42 090 and

Table 11. Standardised mortality ratios (SMRs) for lung cancer (1977–1993).

Group interval	Expected	Observed	SMR	95% confidence
Dust-exposed miners	3.3	17	5.15	3.36–7.89
Dust-unexposed miners	3.5	8	2.30	1.17–4.51

26 953, respectively. The age-specific lung cancer mortality rates used to obtain the expected numbers were obtained from the book *An Investigation into Death from Cancer in China* [13].

The reasons that our epidemiological study was limited to lung cancer mortality are as follows. According to the work of Stehney [8], the adjusted concentrations of ^{232}Th in autopsy samples (mBq g^{-1}) were as follows: lung, 67.1; pulmonary lymph nodes, 1210; bone, 0.58. In 1987, Shawkia *et al* [9] reported that the thorium contents of human tissues (pCi kg^{-1}) were as follows: lung, 0.58; lymph nodes, 7.8; skeleton, 0.16. The assigned tissue weighting factor (w_T) for LN_{Th} (lymphatics) is only 0.001, much lower than that of BB (bronchial) 0.333, bb (bronchiolar) 0.333, and Al (alveolar–interstitial) 0.333 [10]. Further, the w_T for the lung is 0.12, while the w_T for the bone surface is only 0.01 [11]. Consequently, we decided to select respiratory diseases and specifically cancers of the lung to be the principal end point for investigation.

In the unexposed miners (including staff) the age distribution is different from that of the exposed miners: the proportion of elderly men among the unexposed miners is much higher than that among the exposed miners. This is the reason why the expected number of lung cancer deaths in the dust-free miners is greater than that in the dust-exposed miners, even though the number of person-years is much less.

Table 11 shows that both the SMR for the dust-exposed miners and the SMR for the unexposed miners are significantly greater than unity. The SMR for the dust-exposed miners is greater than that for the controls, and the difference is marginally significant ($P = 0.04$) [12].

At present, serious health effects have not been reported for inhaled thorium, as distinct from injected thorotrast (containing ^{232}Th). There is inadequate evidence in humans for the carcinogenicity of ^{232}Th after inhalation, but thorium and thoron (^{220}Rn) progeny can be considered as potential health hazards by analogy with the known effects of radon (^{222}Rn) progeny in man and plutonium in animals. According to our investigation, the SMR for lung cancer in the thorium-containing-dust-exposed miners in this mine is higher than that for the unexposed miners (5.12 versus 2.30). However, the average thorium lung burden of the dust-exposed miners is only 1.8 Bq.

Using the LUDEP [14] implementation of the ICRP Publication 66 lung model [15] it may be estimated that long term (tens of years) inhalation of ^{232}Th, assuming an activity median aerodynamic diameter of 5 μm and class S solubility behaviour, results in an accumulated lung burden of 0.16 Bq per Bq y^{-1} of intake. We may, therefore, interpret the lung burden of 1.8 Bq as reflecting a constant chronic inhalation intake of about 11 Bq y^{-1}. If we assume that the inhaled dust contains ^{232}Th, ^{228}Ra, ^{228}Ac, ^{228}Th and ^{224}Ra in secular equilibrium, an intake of 11 Bq y^{-1} corresponds to a committed equivalent dose to lung of 3.4×10^{-3} Sv y^{-1}, and the average exposure time of 28 years for the dust-exposed miners indicates an average individual cumulative committed equivalent dose to lung of 9.5×10^{-2} Sv.

If we take an excess risk coefficient for lung cancer mortality of 4.0 (95% confidence interval: -1.5, 9) per 10^4 person years per Sv, based on the Hiroshima and Nagasaki Life Span Study [16], the 42 090 person-years of follow-up for the dust-exposed miners, together with the average individual cumulative committed equivalent dose to the lung of 9.5×10^{-2} Sv, would lead to an expectation of only 1.5 excess lung cancers. This is much lower than the 13.7

excess lung cancers listed in table 11. However, 78% of the miners were smokers, and the role of smoking in the mortality rate for lung cancer must be taken into account.

Doses can also be couched in terms of working level months (WLM). According to ICRP Publication 32 [18], the relationship between WLM and Sv is 0.064–0.17 Sv/WLM. For mine areas with high dust concentrations a dose factor in the lower part of this range would be expected. Therefore, we assume that 1 WLM is equivalent to 64 mSv, so that the average individual cumulative committed equivalent dose to the lung is 95 mSv, equivalent to 1.48 WLM. We conclude that the average individual cumulative exposure to thorium is equivalent to 1.48 WLM.

According to Xu [19], the average annual exposure from thoron progeny in the mine is 1.84 WLM. Using the conversion factor from ICRP Publication 47 [20], the predicted number of excess lung cancer deaths for 42 090 person-years is 1.10, also much lower than the 13.7 excess lung cancer deaths listed in table 11. Therefore, it is difficult to conclude that the SMR for lung cancer mortality among the dust-exposed miners is due only to the long-term inhaled thorium and thoron progeny.

In 1996, IARC [21] reported that there is sufficient evidence in humans for the carcinogenicity of inhaled crystalline silica in the form of quartz or cristobalite from occupational sources. As mentioned above, the content of SiO_2 in the dust is much higher than that of ThO_2 (10% versus 0.04% by weight). So, there is good reason to consider that SiO_2 is an important factor in inducing the excess lung cancers among the dust-exposed miners in this mine during the period from 1977 to 1993.

As an estimate, among the 17 deaths from lung cancer among the dust-exposed miners, about two cases are predicted to be due to radiation exposure from inhaled thorium and thoron daughters, eight cases are due to the smoking (comparable with eight cases among the dust-free miners) and the remaining seven cases could be due to the inhaled SiO_2.

The percentage of smokers among the miners (78%) [22] is much higher than that for males in whole population of China (66.9%) [23]. Further, bad weather and poor nutrition in the mine area might worsen the situation. It is suggested that these factors, in particular smoking, are the reasons for the elevated rate of lung cancer mortality in both dust-exposed and dust-unexposed miners.

In 1979, Panomareva found a synergistic effect between exposure to dust, ThO_2 and chronic γ exposure [24]. Therefore, for the excess lung cancer deaths among the exposed miners from the crushing workshop, an enhancing effect of chronic γ exposure cannot be ruled out.

The percentage of smokers, smoking history and cigarettes per day among the miners from the crushing group were not significantly different from the internal control group (table 3), and these data suffice to exclude the confounding effects of smoking in the causation of the observed excess of mortality from lung cancer in the dust-exposed miners.

In summary, the higher SMR for lung cancer mortality among the dust-exposed miners is likely to be due to long-term exposure to ore dusts (containing the carcinogens ThO_2 and SiO_2) and thoron progeny. The enhancing effect of chronic γ exposure in the dust-exposed miners cannot be excluded.

4. Conclusions

(1) The average thorium lung burden estimates for those 64 miners from the high-dust-generating workshop—the crushing workshop—is at a level of 1.71 ± 0.18 Bq, with a range from 0.13 to 7.26 Bq. This average value is significantly different from the average thorium lung burden estimate, 0.58 ± 0.04 Bq (range from 0.11 to 1.45 Bq), for

the 72 miners from the other six low-dust-generating workshops in the same mine. The latter group was treated as an internal control group in this study.

(2) Comparison of respiratory symptoms between the above-mentioned two groups showed that the incidence of severe breathlessness in the crushing group is significantly different from that in the internal control group (32.8% versus 13.9%; $\chi^2 = 6.898$, $P < 0.01$). This might be due to the long term inhaled high concentrations of thorium-containing ore dusts, mainly the SiO_2 component, which induced fibrosis of lung tissue.

(3) The incidence of pneumoconiosis of stage 0^+ in the crushing workshop group is 18.75%, which is highly significantly different from that in the internal control group, 1.40%. Owing to the very low content of thorium in the dust (0.04%), the authors suggest that the chemical constituents, such as silica (10%) and rare-earth elements, might be the main factors in inducing fibrosis of lung tissue [7].

(4) The results of the four haematological parameters and the four hepatic parameters for the 136 miners examined are all within the normal range. This indicates that the proportions of thorium-containing ore dusts entering the blood circulation and deposited in the liver are small, which may be expected from the low solubility in the lung of ThO_2.

(5) An epidemiological study showed that the SMR of lung cancer mortality in both the thorium dust-exposed miners (SMR = 5.15) and the thorium unexposed miners and staff (SMR = 2.30) were higher than unity.

(6) The higher SMR of lung cancer mortality in the dust-exposed miners is likely to be due to the long-term exposure to thorium-containing dusts (carcinogens are ThO_2 and SiO_2) and thoron progeny. As calculated radiation doses from the exposures do not account for the observed lung cancer excess, the most important factor may be exposure to SiO_2. The enhancing effect of chronic γ exposure on the dust-exposed miners in the mining workshop cannot be excluded.

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